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Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration

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ABSTRACT

This paper presents a comprehensive review and assessment of the latest research and advancement of electric vehicles (EVs) interaction with smart grid portraying the future electric power system model. The concept goal of the smart grid along with the future deployment of the EVs puts forward various challenges in terms of electric grid infrastructure, communication and control. Following an intensive review on advanced smart metering and communication infrastructures, the strategy for integrating the EVs into the electric grid is presented. Various EV smart charging technologies are also extensively examined with the perspective of their potential, impacts and limitations under the vehicle-to-grid (V2G) phenomenon. Moreover, the high penetration of renewable energy sources (wind and photovoltaic solar) is soaring up into the power system. However, their intermittent power output poses different challenges on the planning, operation and control of the power system networks. On the other hand, the deployment of EVs in the energy market can compensate for the fluctuations of the electric grid. In this context, a literature review on the integration of the renewable energy and the latest feasible solution using EVs with the insight of the promising research gap to be covered up are investigated. Furthermore, the feasibility of the smart V2G system is thoroughly discussed. In this paper, the EVs interactions with the smart grid as the future energy system model are extensively discussed and research gap is revealed for the possible solutions.

Contents

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1. Introduction

In the world today fossil fuels are the dominant energy sources for both transportation sector and power generation industry. Depletion of fossil fuel reserves gives a wakeup call for finding the alternative energy sources for these sectors. In fact, the future of oil economy which is considered to be highly dependable by vehicle fleets in the world is not only unsustainable but also very limited. Besides, burning fossil fuels produces greenhouse gases (GHGs) which highly influence the world climate change. According to the report [1], the oil consumption in transport sector will raise by 54% until the year 2035. Also the projection by Energy Information Agency (EIA) reveals that the oil prices will substantially rise in the next two decades. In this context, various efforts related to reducing oil consumption have emerged. In the transportation sector, electric vehicles (EVs) are the promising solution and they are taking a remarkable pace in the vehicle market. In the future, the economic studies predict a replacement of the internal combustion engine vehicles (ICEVs) with the EVs. The Australian Energy Market Commission (AEMC) projection shows up that by the year 2020 the growth in the EV's share of new vehicle sales will increasingly account for less than 10%, and it will further account for 15% to 40% increase of the new light vehicle sales after the year 2020 [2]. Much effort has to be devoted to reach the future EV market projections as they feature high initial cost compared to the ICEVs.

On the other hand, the electrification of transportation sector appears to be one of the feasible solutions to the challenges such as global climate change, energy security and geopolitical concerns on the availability of fossil fuels. The EVs are potential on serving the electric grid as independent distributed energy source. It has been revealed by some studies that most vehicles are parked almost 95% of their time. In this case, they can remain connected to grid and be ready to deliver the energy stored in their batteries under the concept of vehicle to grid (V2G) introduced earlier by Kempton [3].

To this end, the EV technology can provide the grid support by delivering the ancillary services such as peak power shaving, spinning reserve, voltage and frequency regulations [4] whenever needed. Besides, the integration of large renewable energy sources (RES) like wind and photovoltaic (PV) solar energies into the power system has grown up recently. These RES are intermittent in nature and their forecast is quite unpredictable. The penetration of the RES into the power market is enormously increased to meet the stringent energy policies and energy security issues.

China for the year 2020 has set a goal to install 150–180 GW of wind power and 20 GW of PV solar power. This huge penetration of the RES into power system will require large energy storage systems (ESS) to smoothly support electric grids so that the electrical power demand and operating standards are met at all the times [5]. In this case, the EV fleets are the possible candidate to play a major role as the dynamic energy storage systems using the V2G context. To this point, the EVs can be aggregated and controlled under the virtual power plant (VPP) concept model [6]. While the EVs are providing these opportunities through charging and discharging of their battery packs, a number of challenges are imposed to the power system grid. These challenges compel the changes on the planning, operation and control of the electric grid [7]. To the utility, the EVs are both the dynamic loads which are difficult to schedule but also a potential back up for the electric grid. Similarly, the vehicle owners have some notion that possessing an EV will substantially increase an extra operating cost when compared to owning an ICEV. Hence, an attractive scenario is needed to merge them so that a sharing of load can be realized between the two parties.

However, as the majority of the people witness and become aware of the contemporary penetration of the EVs, they would require knowing how much it costs for recharging their vehicles and find a way to minimize charging costs similar to their usual ICEV refueling practice. On the other hand, a cost for selling power to the grid should instantaneously be known by the vehicle owners or EVs fleet operator/aggregator in the case of providing V2G services. Furthermore, the aggregator has to know in real-time the characteristic parameters (i.e. driving patterns, state of charge, total capacity, etc.) of the aggregated EVs for the network management response such as demand side management issues, frequency regulation and other ancillary services [8]. Definitely, this demonstrates how the EVs would change the way we daily understand and interact with the electric grid. The cost of electricity will be sensitive and determinant factor for the EV owners or energy market players to interact with the grid while the load profile will dictate on the grid operator (GO) side.

With the deregulated power market, the real-time-pricing scenario is quite intuitive but it requires advanced metering, information and communication control systems. This is shifting the existing grid to the future electric grid network mostly referred to as smart grid where the EVs as dynamic loads and potential energy buffer (i.e. dynamic ESS) can be accommodated. In the smart grid infrastructure, the real-time pricing and communication are conceivable through smart metering and advanced information and communication technology (ICT) [9]. Intelligent scheduling of the EV charging is also attainable to relieve the stresses on the power distribution system facility. These mutual relationships between the EVs and smart grid make a perfect match for a modern power system model.

To further identify and potentially utilize these aforementioned opportunities a clear understanding of an integrated framework of the EV niche market, distributed RES and electric power grid is vital and indispensable. This paper extensively reviews and assesses the EVs interactions with the smart grid infrastructure as the future energy system model. A research gap is discussed to unveil possible solutions and the EV-V2G future research trends are uncovered. The integration of the renewable energy sources especially wind and PV solar using the EVs is evaluated in the light of the latest research works. We also examine the feasibilities of the V2G transactions under the recent pilot projects and demonstrations. For the purpose of this study, the battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) can be referred to as electric vehicles (EVs).

The paper is organized as follows: the integration of the EVs into the power system under the V2G concept and its realization within the VPP phenomenon are reviewed and discussed in Section 2. On the other hand, Section 3 extensively assesses the interaction of the EVs and smart grid with the focus on the smart charging and advanced metering and communication infrastructures. An intensive review on the integration of the RES using EVs is presented in Section 4. Moreover, Section 5 evaluates the feasibility of the EV integration in the smart grid infrastructure with an insight of the relevant current and future projects. Also the general EV and V2G future trends are unveiled in this section. At last, the conclusion is drawn in Section 6.

2. EVs integration into electric grid

Integration of a large number of EVs into the electric power system is a major challenge which requires an intensive assessment and observation in terms of economic impacts, operation and control benefits at optimal conditions. Many existing literatures analyzed the impact of the EVs on the distribution power system [10] while others dig-down the different application

models on how to realize this EVs adoption into the power system [11]. Based on the recent studies, the majority of the EV charging systems are conceived to be undertaken at home. On the other hand, the EV charging is also foreseen to be mainly taking place in the public, commercial or working place charging stations [12]. Therefore, the consequences of the EV charging are expected to directly affect the electric power distribution system. These effects range from overheating power transformers to incurring new investments of power distribution facilities. However, the adoption of the EVs can be able to extensively add value in the electric grid in terms of performance, efficiency and power quality improvements. This is possible if at all the large number of the EVs integration is well planned and technically reorganized to conform to the power system operational standards [13].

To realize the actual benefits of integrating large EV fleet into the electric grid, different approaches have been proposed in the literatures. The backbone of this scenario is of two folds, that is, the electric vehicle owner and utility entity. More importantly, both parties can enjoy the system interaction at the expense of advanced control, ICTs and operation compromises. The most common architecture explicitly involves the EV aggregator and it has gained interests to the researchers in the recent years [14]. The aggregator is considered to be a central in-charge who coordinates all the required operational activities like communicating with the distribution system operator (DSO), transmission system operator (TSO) and energy service providers. In most cases, the aggregator maintains the link between energy market players and the EV owners. Besides, the realization of this EV integration can be conceived within the virtual power plant (VPP) concept in which the electric vehicles are clustered and controlled as a single distributed energy source [15]. Within the VPP architecture, the EVs are visible to the DSO, TSO or grid operator (GO) through the aggregator and can easily participate in the energy market. On the other hand, another possible solution is to integrate large EV fleet in the sense that individual vehicle owners play a central role to participate in the energy market [7,16]. This means that the EV owner is dedicated to manage the queries from the DSO, TSO and/or energy market players with the help of the two-way communication and control systems. Recent literatures have presented this model of the EV integration by optimizing charging price so that the EV owner can minimize the charging cost at all times while reducing the stresses on the power grid [16]. With this integration scheme, the aggregator as a third party is not completely isolated but rather indirectly involved. This can be manifested with the price responsive bids in the energy market. However, to some extent this integration scheme might not be reliable because dealing with each individual EV owner increases the complexity in energy planning, security and control. To be more precise, the optimization function becomes complex with uncertainties.

It is noted that the battery technology dictates the EV penetration into energy market. The battery technology involves numerous chemistries such as lithium-ion (Li-ion), lead acid and nickel metal hydride (NiMH). The center for the massive penetration of the EVs into the world power market and transportation industry relies mainly on the intensive research in the battery technology. It is well known that this poses more challenges towards the initial cost reduction, vehicle performance (e.g. driving range) and high profit margin in the power market. In the V2G application, the battery lifetime is highly affected due to imposing frequent charging and discharging cycles. This effect has become prominent and gained interests by researchers recently [17]. The interesting study by Peterson et al. [18], investigated the capacity fade characteristics of the lithium-iron-phosphate ($LiFePO_4$) battery cells when deployed in both V2G and normal driving modes. The battery loss capacity was quantified as the function of the driving days, combined energy usage and battery capacity. The study revealed that this type of battery sustains the frequent charging–discharging cycles with very minimal capacity loss. Guenther et al. [19] conducted a study to examine the battery degradation characteristics of the Li-ion battery based on the aging model. The loading behavior took into account various combinations of driving scenarios, charging schemes and peak shaving (V2G transaction). The results show that V2G transactions reduce the battery lifetime for nearly 3 years because of the prolonged discharging cycles and greater cycle depths. However, the battery life can be extended by adopting intelligent charging schemes. More studies are required to unveil the other battery life span behavior under these promising EV application scenarios especially the V2G transactions. The realistic battery model for these studies should consider calendar aging, self-discharging and aging cycles as whole. The future expectation is to have the batteries with high energy and power capacities, small size and affordable purchasing cost. Table 1 presents the current battery technologies used by various automotive manufacturers.

To this end, a real time-advanced communication is a vital ingredient for the information exchange especially pricing, energy forecast and EV-driving characteristics among parties. Hence to successfully operate this scenario, the smart grid platform is indispensable. In smart grid implementation, an advanced communication infrastructure can be easily accessed and make it a potential moving target for the EV penetration into the energy market. The subsequent sections will give a detailed review on these electric vehicles to smart grid interaction scenarios.

2.1. EV charging and electric grid interaction

EV charging is one of the fundamental schemes in the electric vehicles' applications. There are several charging levels for EVs that reflect the power capability and charging duration. These

Table 1
Battery capacity and technologies by various EV manufacturers.

S/N	Car model/EV type	Company	Battery chemistry	Capacity [kWh]
1	Chevrolet Volt/PHEV	GM	Lithium manganese oxide spinel Polymer (LMO spinel)	16.5
2	Prius Alpha/PHEV	Toyota	NiMH	1.3
3	Prius (ZVW35)/PHEV	Toyota	Lithium nickel cobalt aluminum oxide (NCA)	4.4
4	Leaf/BEV	Nissan	Lithium manganese oxide (LMO)	24
5	iMiEV/BEV	Mitsubishi	Lithium manganese oxide (LMO)	16
6	E6/BEV	BYD	Lithium iron phosphate (LFP)	75
7	Tesla model S/BEV	Tesla	Lithium manganese oxide (LMO)	85
8	Chevrolet spark/BEV	GM	Nano lithium iron phosphate (LFP)	21.3
9	Fiat 500e/BEV	Chrysler	Lithium iron phosphate (LFP)	24
10	Honda Accord/PHEV	Honda	Lithium manganese oxide (LMO-NMC)	6.7

Table 2
AC/DC charging levels characteristics as per SAE J1772 standard.

Power level type	Voltage level [V]	Current capacity [A]	Power capacity [kW]	Remark(s)	
AC Level 1	120VAC	12	1.4	1-phase supply (EV contains an on-board charger)	
		16	1.9	Charging time	PHEV: 7 h
					BEV: 17 h
AC Level 2	240VAC	Up to 80	19.2	1 or 3-phase supply (EV contains an on-board charger)	
				3.3 kW charger	PHEV: 3 h
					BEV: 7 h
				7 kW charger	PHEV: 1.5 h
					BEV: 3.5 h
AC Level 3	–	–	> 20	Under development	
DC Level 1	200–500VDC	< 80	Up to 40	3-phase supply (EVSE contains an off-board charger)	
				20 kW charger	PHEV: 22 min
					BEV: 1.2 h
DC Level 2	200–500VDC	< 200	Up to 100	3-phase supply (EVSE contains an off-board charger)	
				45 kW charger	PHEV: 10 min
					BEV: 20 min
DC Level 3	200–600VDC	< 400	Up to 240	Under development	

levels have been standardized to reveal the EV slow or fast charging scenarios. The slow charging (typically up to 8 h-PHEV or 20 -BEV) can be experienced at home or office areas whereas the fast charging (typically 15 min to 1 h) at dedicated charging stations in commercial or public places. As shown in Table 2 [20], the AC Level 1 is practically realized at home environment while the AC Level 2 is suitable for public and commercial areas like workplace, movie theaters, shopping malls etc. However, the DC-fast charging (DC Level 1–3) is envisioned to cover the public, private or commercial charging stations [20,21].

The charging power delivered is usually determined by the nominal ratings of the battery charger and in most recent studies the EV battery voltage is typically limited to a less or equal to 400VDC (DC bus voltage). Also, the charging time that the EV can spend fully charging its battery pack may vary depending on the battery storage capacity and charging level characteristics (voltage and current ratings). There is a great debate on how to standardize the fast charging portfolio. However, fast charging is essential for charging the EV battery within few minutes. The recent development of a universal charging facility accomplished by the global automakers in collaboration with the Society of Automotive Engineers (SAE) incorporates both the AC charging and DC-fast charging solutions. It combines AC single-phase charging, AC three-phase charging (AC-fast charging) and utra-fast DC charging in a single unit connector (SAE combo standard). Besides, the fast charging standard known as CHAdeMO, which was developed by the Tokyo Electric Power Company (TEPCO), is also attaining a remarkable acceptance in the EV market [21]. This will attract the adoption of the EVs as a reliable transport facility as it will mimic the fast ICEV refueling phenomenon. The recent study by Chaundhry and Bohn [22] proposes an overview of the V2G application using DC fast charging Level 1 supporting up to 36 kW, Level 2 up to 90 kW and DC fast charging with the CHAdeMo standard capable of delivering power up to 62.5 kW. This is one of the attempts to unveil the feasibility of the V2G using the DC fast charging infrastructure. In this study the AC Level 1 and 2 are also investigated.

However, the current power system is supplying the AC voltages to the loads. In order to supply power to the EV battery pack, a rectifier power circuit is mandatory. But the cost and thermal issues limit the power capability of the rectifier circuit. Noting that, the DC-fast charging infrastructure requires high power capability (in terms of current and voltage ratings) as can be observed in Table 2. In this case the size and volume of the rectifier circuit have a great impact on the DC-fast charging infrastructure as it reflects the circuit dimensions to be used for the EV application. There are very few literatures that account for the feasibility, impacts and economics of the DC fast charging solution. In the decade to come this type of EV charging will be the most promising charging solution and the stations will be visualized as existing gasoline refilling stations. The challenge remains, being high power demand from these stations which would require a dedicated power supply, power conversion interface modeling and battery life span. And it is posing a great challenge on the deployment of the V2G services. Feasibility studies are required to unveil the features and performance of the DC fast charging infrastructures for the V2G services.

The revised version of the SAE standard J1772 released in October 2012 [20] introduced more flexibility to accommodate the EVs particularly for the V2G and charging solutions in the smart grid environment. This includes the DC fast charging levels, electric vehicle supply equipment (EVSE) requirements and reverse energy flow communication portfolios for the PHEVs. And the National Electrical Code (NEC) in article 625 (NEC 625) and IEC 62196 cover other details on the EV charging systems. The advances in bidirectional power converters for electric chargers with low electromagnetic interference (EMI) to support the V2G will now may be standard for the EVs. Figs. 1 and 2 illustrate the EV charging configurations for the AC Level 1 & 2 requirements (EV includes an on-board charger) and DC Level 1 & 2 (electric vehicle supply equipment (EVSE) includes an off-board charger), respectively. The two figures illustrate the setup of the facilities at the charging point and embedded EV kits for charging scenarios by considering the AC and DC charging levels as depicted in Table 2. With the AC Level 1 and 2 configurations in Fig. 1, the electric vehicle supply equipment (EVSE) is provided at the charging point by supplying the AC power to an on-board charger. However, with the DC Level 1 and 2 configurations in Fig. 2, the charging point supplies the DC current to the EV battery pack.

With the current EV battery technology such as 24 kWh battery pack for Nissan Leaf, to recharge an EV will consume power almost the same as a single household in Europe or US per day. When two or three EVs are connected for charging purposes, there is a proportional growth of the energy usage. Hence, it reflects the increase in the consumption capacity to the existing grid infrastructure. The authors in [23] surveyed various issues regarding the electrification of the transport sector. They include the policies to foster the EV adoption, charging infrastructures and standards. The study reported that the 3.3 kW charger used at 220 V/15 A would increase the current demand of the household by 17–25%. Different charging schemes have been discussed recently regarding the driving patterns of the vehicle owner and existing grid

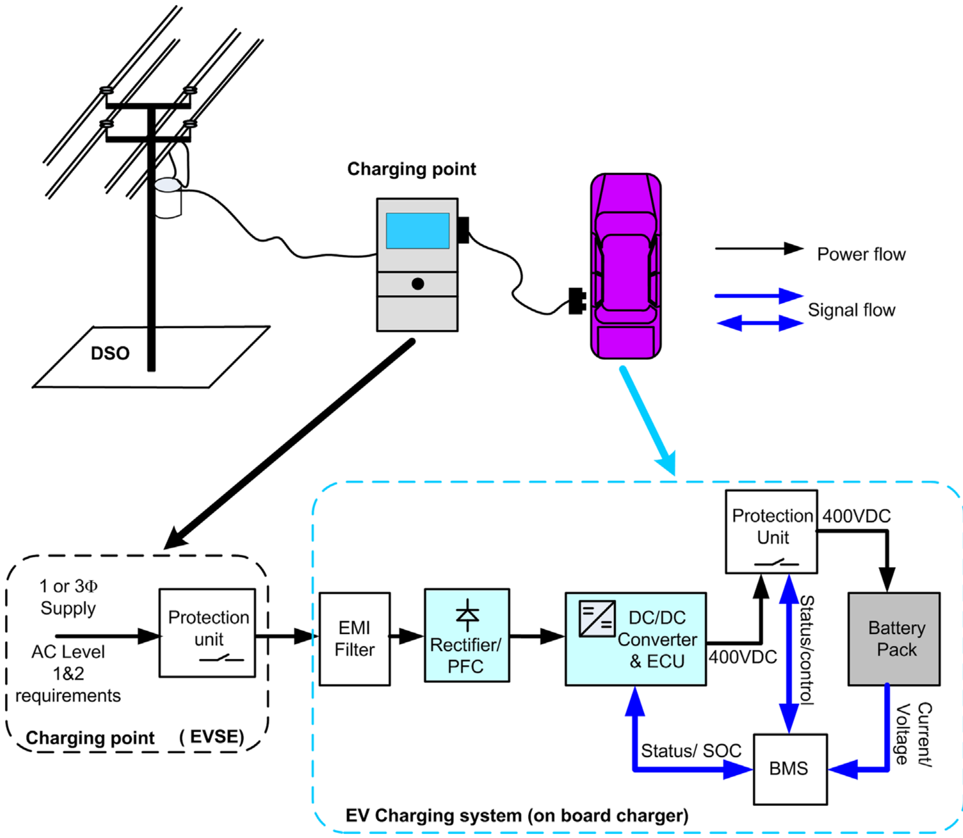

Fig. 1. EV charging configuration at AC level 1 and 2 setup (i.e. onboard charger).

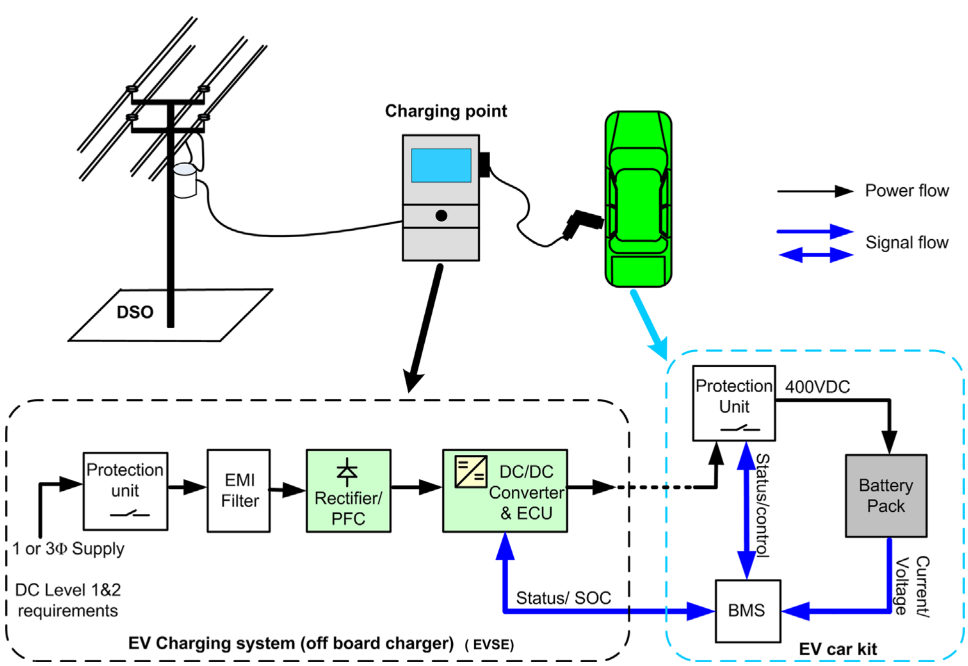

Fig. 2. EV charging configuration at DC level 1 and 2 framework (i.e. off-board charger).

model. These schemes include uncontrolled (dumb) charging, dual tariff charging and smart or intelligent charging [24]. In uncontrolled charging scheme, an EV starts charging immediately when connected to the electric power. Numerous studies have been conducted to assess the impact of this type of charging approach on the power system networks [25]. Almost all studies concluded that this kind of charging increases the overloading and investment cost of the power distribution system.

As mentioned in the previous subsections, the impacts of the EV loading are substantially realized on the power distribution system level. The EV charging increases an additional burden on the existing power distribution grid. If this additional load is not appropriately controlled, it can result to further aging of the power system equipment and tripping of the relays under rigorous overload conditions. It is reported in [26] that up to 60–70% of the required incremental investment cost in the power

distribution system facility can be circumvented if the EV smart charging schemes are adopted. Similarly, one of the mitigations used to safely operate the distribution system while accommodating the large size of the EVs penetration is by shifting this extra load to a valley period or to optimize the available power using the coordinated charging schemes. In this case up to 5–35% of the essential investment cost have been reported to be avoided by load shifting practice with the energy losses up to 40% of the actual values [26]. The authors have devoted much time to studying the loading behavior of the power distribution system following the EVs charging consequences while considering a large scale distribution networks.

2.2. EVs with V2G system architecture

Electric vehicles can be integrated into power systems and operate with different objectives such as the dynamic loads by drawing power from the grid (during charging) or dynamic ESS by feeding power to the electric grid. It is worth mentioning that the latter is referred to as vehicle to grid (V2G). The limited EVs as resources, their spatial-location and low individual storage capacity make them unrealizable for the V2G services. In this case, a large number of EVs are aggregated in different ways depending on the control schemes and objectives to realize the V2G concept [27]. The aggregation of the EVs as a single controllable distributed energy source can participate in energy market for supporting electric grid in regulation and system management.

The interaction of EV with smart grid can realize V2G services through bidirectional power flow or unidirectional power flow. The former means the electric power can flow from the vehicle to grid (V2G) and the grid can send power back to the EV at the time of charging. Most of the literatures have investigated the economics and feasibility of this mutual interaction between the grid and aggregated EVs [28]. Extensive safety protection measures such as anti-islanding and system cost are among the demerits reported to reduce full benefits of this system architecture. On the other side, the unidirectional configuration offers power flow in only one direction, from the grid to EV (only to charge the battery but not to discharge it) [29]. Studies have shown that in this configuration, the EVs can participate in the energy market and provide ancillary services like frequency and voltage regulation. Fsugba and Krein [30] examine the cost–benefit analysis of the V2G transaction when the EV supplies regulation services to the grid using both aforementioned power flow scenarios. In this study, a comparison of maximum hourly regulation capacity for the EV systems that employed a unidirectional charger (UC) and bidirectional charger (BC) was made. It was revealed that the battery with UC has to double its capacity to match the same demand that the battery with BC could supply for grid support. To be more precise, the case study involved the battery with 20 kWh stored energy using the BC to support the regulation capacity of 6.6 kW and the battery with 20 kWh energy request employing the UC managed to support a maximum regulation capacity of 3 kW. Furthermore, the annual revenue acquired by the bidirectional charger (battery capacity fade taken into account) is 12.3% more as compared to the unidirectional one. With issues like protection and metering systems, the extra revenue earned by the bidirectional power flow architecture can be nullified to negative. It is concluded that almost all the V2G benefits acquired by using bidirectional power flow can also be achieved by adopting unidirectional power flow. Further studies are however required to demonstrate the viability of the unidirectional power flow over its counterpart in the areas such as lower power capacity for the V2G transactions.

Meanwhile, the conceptual framework of the VPP offers an aggregation scenario that eases control and information exchange between the utility entity (control center) and the EV fleet to facilitate the V2G realization. Different schemes of the VPP frameworks in the V2G context can be modeled depending on the control philosophy and aggregation type to meet the grid and EVs integration challenges. The control approach in the VPP can be centralized, hierarchical or distributed. In centralized control scheme the decision making and data exchange are based on the VPP central control center (VPPC) while in the distributed control scheme the decisions and flow of information are fully achieved in the distributed manner. On the other hand, the hierarchical scheme includes some decision making and information exchange levels within the spatial VPP model [31]. The VPPC makes decisions and provides some modifications of its requests to the VPP resources in real time by utilizing the measured data collected with the smart meters and the updated information from the energy market. The aggregated EV batteries under the VPP architecture can be used to balance the demand and consumption forecast deviations of the electric power grid. Fig. 3 illustrates the VPP control and implementation in the V2G context. Within the electric grid and energy market players, the EV aggregator will operate as a virtual power plant. As depicted in Fig. 3, the clustered EV fleet at charging station provides status like available SOC/available power to the charging management system (CMS) that communicates with the aggregator control center (local VPP control). At the VPP control center the aggregated battery power can be dispatched to provide ancillary services whenever requested by the DSO or TSO. The VPP control center is set to centralize the energy and communication flow management between energy market players (i.e., power customers and producers) and grid operators.

In the Ref. [32] the authors conceptualize the operation of the VPP as an optimized problem to minimize operating cost. It is observed that by operating the EV fleet as both demand side management unit, dynamic load and ESS (through V2G concept) reduces the operating cost by 26.5%. The study considered charging and discharging cycles of the battery pack together with the EV purchasing costs and other various assumed costs.

3. EVs and smart grid infrastructure

Penetration of more distributed energy resources (DERs) into the energy market is shifting the power generation and distribution industries. The DERs feature variability of time and space of the power production and consumption. This makes the energy management of the traditional power grid to be more complex and challenging. Smart grid comes along as a means to enhance power generation and distribution, which is more flexible, efficient, reliable and secured. The smart grid encompasses advanced technologies in communication, smart energy metering and advanced control. And it can offer EVs as dynamic loads and potential dispatchable-distributed energy sources a flexible and optimized deployment in the power industry [33]. Studies have been conducted to assess and realize the smart grid infrastructure for fostering the EVs penetration in the energy market. Standardization of technologies and protocols in electric power distribution communication are the key motives to the implementation of interactive smart grid. Standards and specifications towards interoperability and seamless integration of the EVs into the electric grid have also been released [34].

Besides, an EV through the electric vehicle management system (EVM) receives and sends information to the GO or aggregator and vice versa. The EVM may embed smart meter (SM) as one of its key components to facilitate real time energy measurement, communication and control. Based on the impact of the EV charging, a smart scheduling can be implemented to optimize the available grid power through the advanced bidirectional data exchange in the smart grid context [35].

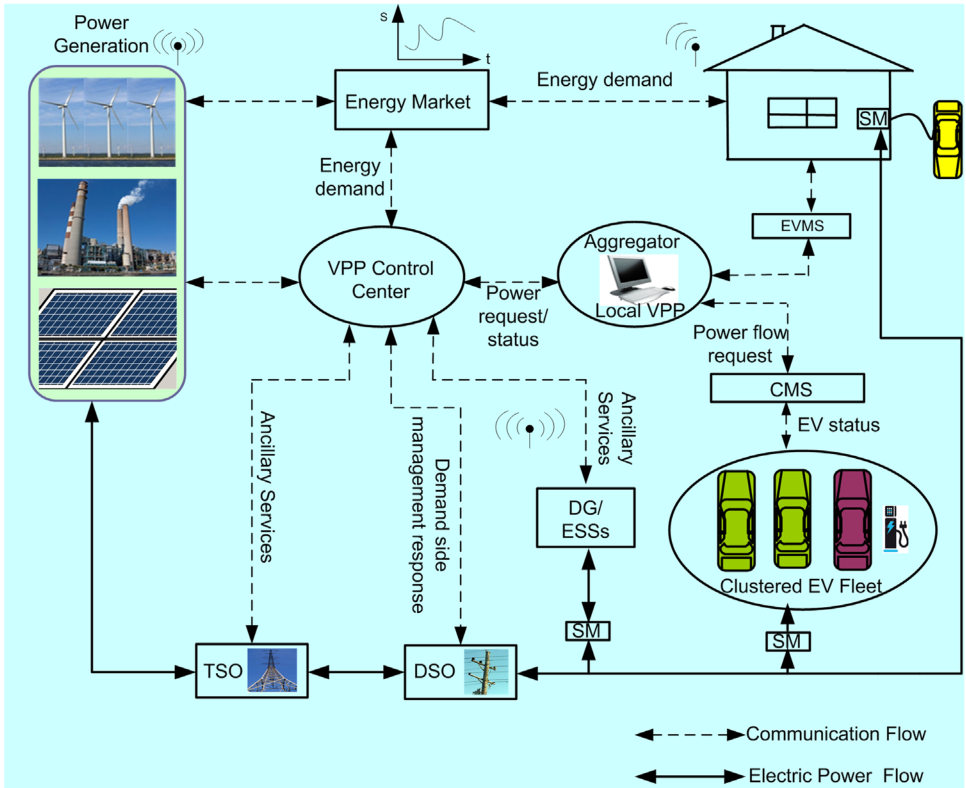

Fig. 3. VPP realization and control in V2G context.

3.1. EV smart charging

In the previous subsections, the potential undesirable impacts of uncontrolled EV charging have been discussed, such as the overloading of the power system facility and increased power demand leading to a less efficient electricity supply. To this end, an important part of the literature has been devoted to intelligent charging schemes (i.e. smart charging) [36]. Smart-charging schemes can pursue various objectives. Some studies focus on the minimization of system or charging costs in the electricity market [37] which in most cases leads to a valley-filling type of charging. Other studies do not model the supply side explicitly but rather try to find some intelligent ways to avoid undesirable impacts on the electric grid network [38]. It has been observed that an optimized algorithm is very crucial to effectively schedule and utilize in an intelligent manner the benefits of the EV niche market. With the large EV penetration into the power systems, many constraints coexist in the real world implementation scenarios which have to be optimized for the better solutions. The constraints are not constant but they do vary depending on the objectives of the deployed EV system, such as minimization of the charging cost, GHG emissions or losses in the power system, a few to mention. The authors in [39] presented a day-ahead energy resource scheduling for smart grid by considering participation of the DERs and V2G. A modified particle swarm optimization approach is used for intelligent optimal scheduling. Besides, the EVs are controlled to respond to the demand response programs. The overall operating cost reduction demonstrates the efficacy of the smart EVs scheduling in the smart grid environment.

An optimized price algorithm pertaining the scheduled EV charging and V2G operation is proposed in [40]. To facilitate this intelligent charging, the Radio Frequency Identification (RFID) tag technology is also used. The authors involve EV owner via web mobile application to acquire information and to have control over the EV charging by using parameters like the desired state of charge (SOC), arrival and departure times or the option for the V2G services to maximize profit. The scheduled charging scheme reported to be cost effective. It resulted in 10% and 7% savings for drivers with flexible charging scheme and enterprise commuters, respectively. In addition, a 56% reduction of the peak power demand is attained with the driver variable charging scheme.

As per [41] a real time approach is proposed to minimize power losses and enhance voltage profile in the smart grid power distribution. The uncontrolled and controlled charging behaviors of the plug-in electric vehicle (PEV) with different penetration are investigated to reveal their impacts on the electric grid. With the modified IEEE 23 kV distribution system, it is observed that high (63%) or low (16%) penetration of the PEV with the uncontrolled charging results in severe voltage deviations of up to 0.83 p.u. (below 0.9 p.u. margin), high power losses and cost in generation. However, with coordinated charging schemes the voltage profile is improved up to 0.9 p.u. and the losses are reduced. Likewise, Ferreira et al. [42] proposed a conceptual smart charging system which relies on the consumption historical statistics with data mining approaches. The charging facility and EV system are interfaced by the web applications capable of running on the mobile devices like smart phones. A mobile device with the GPS-assisted functionality is used to determine the driving characteristics of the EV from which the battery SOC is captured. Nevertheless, there is a slow communication response in this architecture. It would be better all the process information to be handled automatically at the machine level without much involving a third party (i.e. driver) for efficient and reliable operation.

3.2. Advanced metering infrastructure with EVs

Energy management system (EMS) in smart grid is accomplished by measuring, analyzing and reporting the energy use or demand in near-real time phenomenon. Smart metering is a core component in the effort to realize online EMS functionalities in the

smart grid. In the integration of the EVs into the power grid, a smart meter (SM) plays a major role in obtaining the near-real time information of the power demanded or consumed. Hence, the SMs make the process of energy forecast such as day-ahead or intraday forecast and energy pricing more feasible [9,34]. These are the fundamental roles of the SMs in the smart grid operation. To this end, the advanced technologies in the smart metering are necessary to accommodate the dynamic EV loads. Hence, the advanced metering infrastructure (AMI) is a framework that embraces the real time smart metering and communication as a single unit.

In [43], the EV and AMI are listed among the eight priorities to implement an effective smart grid. The AMI system encapsulates various technologies and applications that are integrated as a single functional unit. They include meter data management system (MDMS), home area network (HAN), SMs, computer hardware, software, advanced sensor networks and different communication technologies. The communication technologies in the AMI framework can be wireless or broadband over power line (BPL)/power line communication (PLC) that provides a two-way communication link between the utility network, smart meters, various sensors, computer network facilities and EV management system (EVMS) [44]. The information gathered by the AMI can be used to implement intelligent decision and control system. To this end, the electric vehicle's intelligent scheduling is possible in the smart grid using an effective AMI. In [44], the AMI solution is adopted as a platform for the EV charging system under dynamic pricing and charging schedule scenarios. It is concluded that the deployment of EVs using AMI platform can manage to reduce the peak energy consumption by 36%. It shifts 54% of the energy demand to the off-peak period. Hence, it releases the stresses of the power system during peak demand.

Fig. 4 depicts an overview of the AMI solutions for the EV interactions with the smart grid. It represents collection of information of the energy usage or demanded using SMs. The SMs communicate data collected through the communication technologies like BPLC or WiMAX in a particular Field Area Network (FAN), Local Area Network (LAN) or HAN. In fact, these data are received at the AMI head-end system (i.e. where it performs data validation before making them available) prior to the MDMS which is responsible for the data management, storage and analysis. The EV aggregator or utility can access the energy information through the MDMS. By using consumer web portal; the human machine interface can be realized between the EVMS, MDMS, utility service provider and energy market.

Different functionalities of the AMI such as seamless connectivity, extended data storage and bidirectional power measurement and communication for the EV applications in the energy industry have been discussed in [45]. The authors presented various functionalities for the AMI deployment in the EV charging, V2G services and vehicle to home (V2H) application cases. The AMI solutions in the V2G context will be an effective gateway to deliver universal functions which include both measurement and communication so as to achieve a high intelligent level of energy management.

3.3. *Advanced communication and control network infrastructure with EVs*

A two-way communication network of the smart grid infrastructure enables many demand response technologies, which control a number of distributed energy resources over enormous dispersed geographical areas. In this case, wireless communication is the ambitious solution for the V2G applications. It features low cost and wide area coverage. In the EVs interaction with the smart grid, we anticipate frequent request and acknowledgment modes of communication with various system devices like SMs for successful operation. Depending on the EV integration scheme into the smart grid, communication solutions can be envisioned in two different scenarios. First, the communication link from the advanced sensors and EVMS to the SMs. The second one is being between the SMs and grid operators/aggregators data centers. The former can be accomplished by using PLC or wireless communication technologies while the latter by employing advanced mobile network solutions like 3G, WiMAX and 4G LTE.

However, with the EVs deployment to the power industry, new challenges are brought up on monitoring, communication and control architecture due to its dynamic mobility nature.

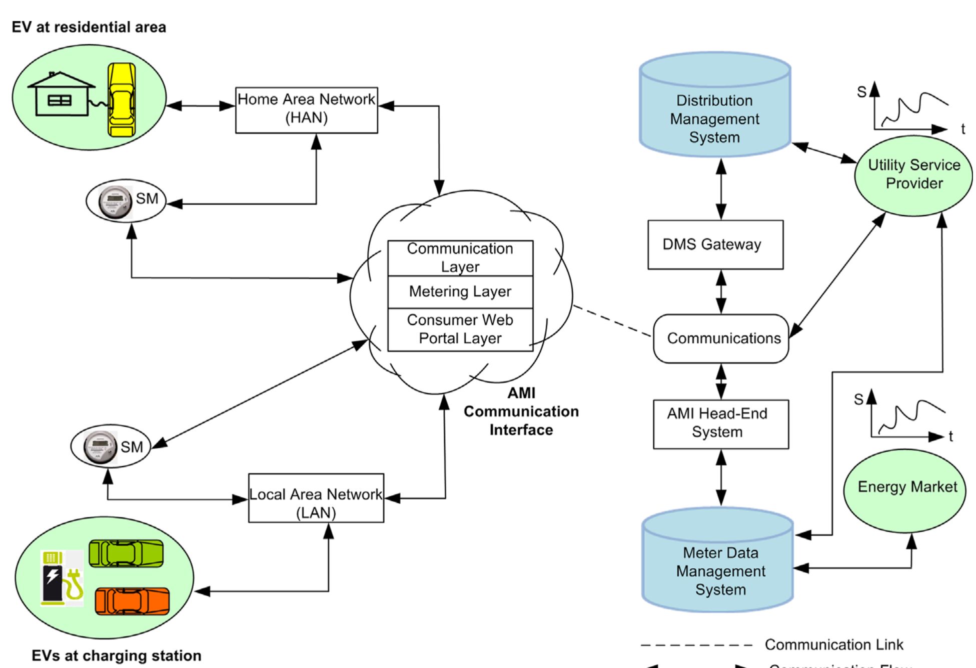

Fig. 4. Overview of the AMI architecture in V2G framework.

For instance, an advanced SM should be able to allow the EV to be connected to a different aggregator, energy supplier or visiting network when it's away from its HAN or LAN. To properly handle these routines an effective communication with wide area coverage should be reliable. As per [46] advanced development in wireless communication appears to favor smart metering facilities. This is an attractive case for the EV applications as most of the EVs are spatially dispersed in the real world. For successful operation of the EVs, they have to be able to connect at any time (wherever charging point is available) for recharging their batteries or supplying power to the grid (i.e. V2G). In this case, the GO or EV aggregator has to be able to identify a particular electric vehicle in the near-real time environment for billing the demanded power. On the other hand, the EV has to obtain the time of use or real time pricing trends from the energy market to deliver power to the grid.

Moreover, wireless sensor network (WSN) is an emerging control network which has gained popularity in smart grid. Recently, some researches have shown promising applications of the WSN in the DG and microgrid (MG) operation. By using the same concept, the wireless sensor network can be adopted to enhance the EV penetration. The challenges are still high in adopting WNSs for the EV applications especially in the V2G services. These challenges include shorter ranges as compared to other wireless technologies, which result in packet delays and decreasing success ratio as the number of hops is increased. In [47] the information system for the V2G application based on the WSN is proposed. The vehicle-grid operator communication is distributed wirelessly to improve the grid demand profile, EV reliability and data delivery with minimum number message broadcast. This study is one of the attempts to realize the advanced EV system with the WSN architecture for supporting V2G transactions. Apart from that, ZigBee technology has been investigated and tested by various researchers, particularly for the EV applications [48]. The ZigBee technology is simple and requires low bandwidth for its implementation. However, the issues like communication interference with other devices sharing the same transmission line, small memory and communication delays need to be addressed to allow ZigBee technology to be reliable and effective for the V2G applications. Table 3 shows the characteristics of some various wireless technologies that can be used for the EV applications such as V2G services.

On the other hand, the cyber-security for the communication network between EV and utility or power market should be assured in order to prevent the smart grid from the cyber-attacks such as price tampering and system congestions by malicious software. These are critical issues as the deployed EV to the grid network is vulnerable as it can easily open doors for cyber-attacks. And it is also necessary to provide secured EV services at the visiting networks. If these aforementioned issues are not taken care they would reduce the effective benefits and reliability of the EVs in the energy market [49]. Fig. 5 shows communication network architecture and functionalities for the EV interactions with the smart grid. The wireless communication technology to be employed depends on the distance between communicating hot spots and the amount of data to be transmitted. In this figure, the smart mobile phone is used as an interface between the EVMS, charging point and aggregator via GPS or/and Bluetooth-enabled functionalities. All the statuses from the EV are communicated to the outside environment through the CAN gateway. The WiMAX protocol represents a long distance communication scenario that covers communication between the aggregator, energy market and utility (TSO/DSO). To increase reliability in the smart grid environment, the Near Field Communication (NFC) protocol can be used to automatically support Bluetooth pairing and intuitively reduce more than eight user interaction to establish Bluetooth connection [50].

Table 3
Wireless communication technologies for V2G applications.

S/N	Technology	Operating frequency	Covered distance
1	ZigBee	868 MHz (Europe) 915 MHz (North America) 2.4 GHz (Worldwide)	10–100 m
2	Near Field Communication (NFC)	13.56 MHz	5–10 cm
3	Bluetooth	2.4 GHz	1–100 m
4	IEEE 802.11p	5.85–5.925 GHz	500–1000 m
5	WiMAX	2–6 GHz	2–5 km

4. Renewable energy sources integration with EVs

The increase in penetration of renewable energy sources (RES) into the electric power system is quite appealing. The existing power grid suffers from unpredictable and intermittent supply of the electricity from these sources especially wind and PV solar energies [5]. The electric power production from these RES can be very high (more than the power demand) or very low (less than the power demand) depending on the available energy sources, i.e. wind speed and sun radiation. In short, these RES are variable with time, nondispatchable with limited control and have low capacity credit especially on the power system planning. Most of the studies revealed that the integration of wind energy conversion systems (WECS) and PV solar systems into the electric power grid is pretty mature and practically viable [51]. However, the promising solution to balance the electricity generation from these RES on the grid can be accomplished by adopting the stationary energy storage systems (ESS) or controllable dispatch loads [52]. The stationary energy storage systems absorb or supply electricity in the case of excess and low power generation, respectively. As this solution involves high investment cost, it delays the high penetration of the RES into the power system or even increases the overall investment cost.

As pinpointed earlier the electrification of the transportation sector is envisioned by the numerous researchers to populate the sector in a decade to come. Then, the EV batteries can be aggregated and act as the ESS that will pivot the integration of the RES into the power market as dynamic energy storage devices. The EVs can absorb the surplus power generated by the RES through different charging schemes or can deliver power to the grid in the low power generation scenarios and level the grid operations through the V2G schemes [53]. To this end, the EVs will be acting like energy buffer for the grid regulations and ancillary services. In [54], it is stated that a possible solution to maintain energy security while reducing GHG emissions can be achieved by integrating the distributed RES (PV solar and wind in this study) and adopting EVs with capability to deliver the V2G services. To simultaneously achieve the GHG emissions and cost reduction, a strategy to optimize maximum utilization of both EVs and RES is required. The authors propose a dynamic optimization approach based on particle swarm optimization. The findings from this study show that for the random charging, the load increases by 10% every year in the power grid but an intelligent scheduling of the EVs (without RES) can solve the problem at the expense of increased cost per day by 1.7% and emissions by 3%. On the other hand, in smart grid mode with both EV-V2G enabled cars and RES, the cost is reduced by 0.9% and emission by 4.3% per day. These results give a glimpse of the perfect match for the interactions

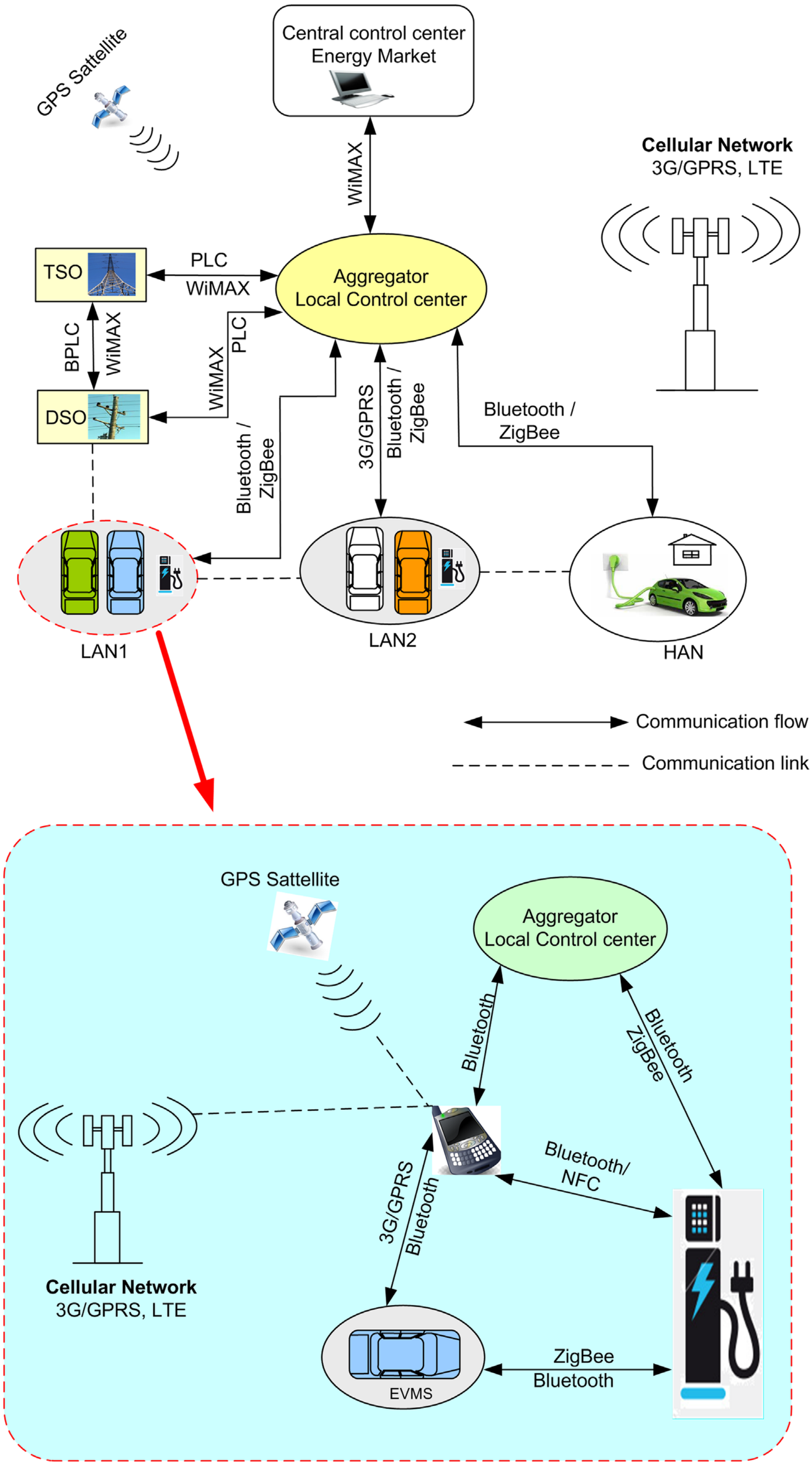

Fig. 5. EV communication network architecture with smart grid.

between the EVs and RESs in the smart grid infrastructure. The subsequent subchapters assess the integration of the PV solar and wind energies using EVs.

Fig. 6 illustrates the integration of wind and PV solar energy sources into the power grid with EVs. The electric vehicles are aggregated at the charging station located at public area or office

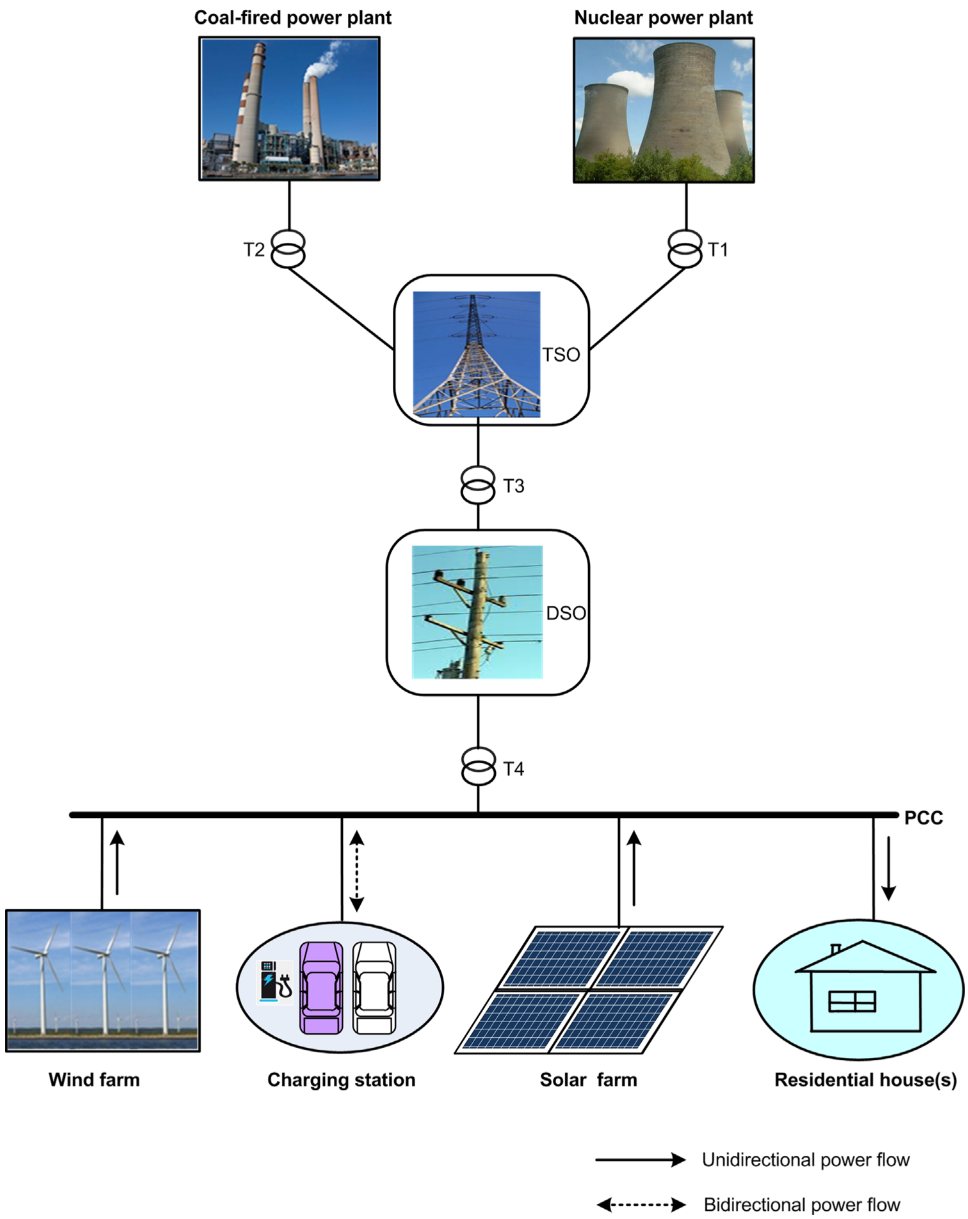

Fig. 6. Wind and PV solar energy sources integration into the electric grid with EVs.

and can be used to suppress power fluctuations from these RES in the V2G mode. In this figure we assume all necessary communication and control schemes are available as described in details in the previous section for the V2G and charging scenarios. In this figure and other subsequent figures T_i stands for the power transformer in the electric grid, where $i=1,2,3,\ldots,n$.

4.1. PV solar energy with EVs

Electricity production from PV solar energy has already shown a promising feasibility. The PV solar arrays are usually clustered to cumulatively provide power to the electric grid. With the EVs penetration getting large share, the PV solar power is more likely to be deployed for charging purposes and grid support. A number of analyses have been presented to show that the deployment of the PV solar on the roof of parking lots for charging EVs is quite appealing [55,56]. Besides, the V2G transactions are also feasible in these PV solar systems [57] and an optimal generation scheduling is possible to reduce operating cost and enhance grid operation as reported in [58]. Tulpule et al. [55] perform the energy economics and emission analysis of the workplace charging station based on the PV solar system by comparing optimal charging schemes with uncontrolled ones. A day-time workplace EV charging behavior under this study considers various data including vehicle parking charges and different parking locations to account for the solar insolation variations. Observations from this study reveal that one vehicle would save 0.6 ton of CO_2 emissions per year by using solar charging at the workplace which amounts up to 55% savings in emissions when employing home charging (night charging at home) scheme. And it reduces 0.36 ton of CO_2 emissions when an optimal charging scheme is implemented, which amounts up to 85% savings in emissions if the home charging scheme is adopted. The SMs and communication infrastructure appear to increase cost for the home charging case and make the PV based workplace charging station a better choice. Fig. 7 depicts the configuration of the standalone solar carport charging station at working place or public area.

In [56] the impact of solar PV arrays built over the rooftop at workplace parking lot to offer charging services for the commuter during day-time is investigated. The study reveals that during

summertime the solar electricity production (up to12.6 kWh) is high and most of the power can be sold back to the grid (V2G) or used at the workplace. This can compensate for some of the investment costs with a bit prolonged payback. On the other hand, during wintertime season, the production (up to 3.78 kWh) is reported to be enough for recharging. The analysis on how to offset the extra cost in the winter is not given though it is important to potentially justify the feasibility. Furthermore, a bidirectional DC charger is modeled in [57] to realize the EV interaction with the power system fed by the PV solar system. The demonstration of the ramp rate compensation for the PV inverter output is also presented. Three scenarios are analyzed in this study: to only charge EV without including any other services (e.g. V2G), EV to provide grid support while charging and EV to offer grid support without involving charging scenarios. The results reveal that the EV charger can offset the huge sudden fluctuations of the PV power due to clouding condition which amounts up to 22.5% of the DC bus voltage per second for the 1.2 kW PV array.

In [58], a generation scheduling scheme that is coordinated with the dynamic PEV charging is investigated in the industrial microgrid (IMG). This scheme encapsulates the distributed RES (with PV solar) and combined heat and power generation. The dynamic optimal power flow (DOPF) approach is proposed to achieve a low operating cost. It is observed that the generation scheduling of the IMG with the PV and PEV significantly reduces the overall operating and charging costs. Nevertheless, the variability of the PV output power can be compensated easily at less expense of communication and control complexity. Fig. 8 depicts a solar carport charging station connected to the electric grid through a bidirectional DC/AC power converter. The two charging stations 1&2 in this figure represent a possibility of having a number of charging points connected to the power distribution. The aggregated EVs at the charging stations 1&2 can support the grid as ESS and provide ancillary services through their bidirectional DC/AC power converters. However, the EVs incorporating the bidirectional DC charger [57] are connected directly at the PV controller and can absorb excess power generated. The DC power system is envisioned to be feasible and attractive solution in the future electric grid model as reported in [59]. In this case, the bidirectional DC charger can be easily accommodated in this electric model. And it can feed back the stored battery power during high demand period when the PV power generation is low.

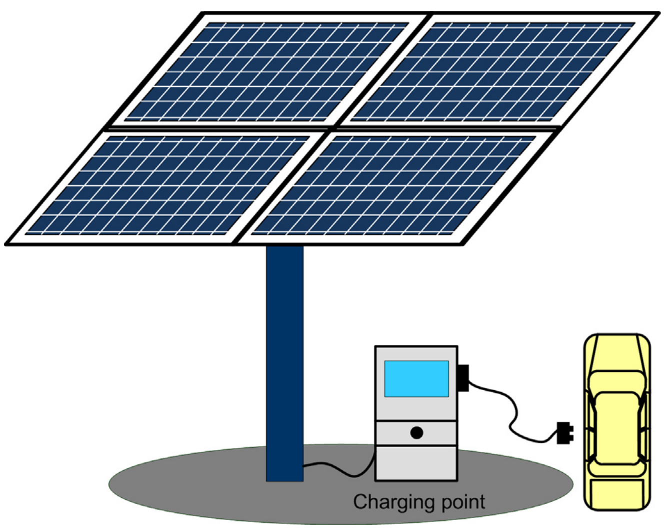

Fig. 7. EV charging station deploying standalone PV solar on rooftop at the parking lot.

The investigation on the large penetration of rooftop PV solar and EVs is reported in [60]. The study is centered on the impacts of the synergy between EV charging and large distributed rooftop PV installations especially with the voltage mitigation support. This mutual relationship works to complement each other; hence the EVs can enhance large integration of the PV solar by providing voltage support and can reduce the stresses on the power distribution system through V2G services. It is noted that a specific integration of PV solar and EVs presented a reduction of about 15% of the voltage fluctuations. The IEEE 123-node feeder was used to characterize a distribution system in a region. However, its stiff condition with relative short distance may not represent the real large power flow scenarios in the existing power system. This gives some perception that a more detailed analysis is required to represent the impact and limitation of the EVs charging and V2G transaction with the large PV solar power to support the grid. Besides, in [61] a potential analysis to deploy PV solar on car parking lots in the Swiss city of Frauenfeld is extensively explored. Results reveal that the installation of the PV solar on parking lots can cover between 15% and 40% of the energy demand of the EVs in the future. The methodology used is simple but it excluded a detailed transportation demand and system analysis. All these

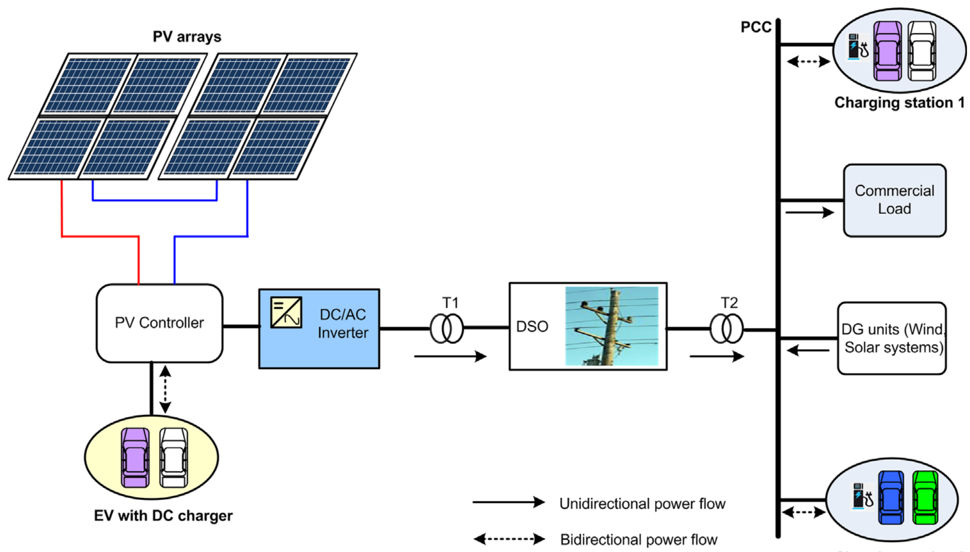

Fig. 8. EV charging station based on grid connected PV solar at the parking lot.

studies have shown a potential mutual relationship on the penetration of both EV and solar PV systems.

4.2. Wind energy with EVs

The concept of using wind energy conversion systems (WECSs) for electricity generation is a prevalent and feasible alternative solution to produce power as discussed previously. The synergy between the WECSs and EVs has been widely investigated by various researchers in different scenarios to deduce their impact and viability onto the electric grid [62,63]. The early study by Lund and Kempton [62] assesses the use of the EVs to provide ancillary services and regulation based on the grid interaction with the WECSs in the US power market. The authors in [63] estimate the amount of wind that can securely be integrated into an isolated electric grid with the vicinity of the EVs. In this study the EVs are considered to participate in the primary frequency regulation and their interactions during smart charging mode are also assessed. The EVs through V2G services support the increase of wind penetration from 41% to 59% in the isolated grid. The study assumes that all the available EVs have intermediate charge and are ready for balancing the grid.

Pillai et al. [64] presented a comparative analysis of an isolated power grid (Danish island, Bornholm) capability to integrate large share of the wind energy system by using hourly-EnergyPLAN model and short duration-dynamic simulation scenarios. The aggregated EV batteries were used under the V2G context for the frequency regulation support. The frequency instability was due to the fluctuations of the large wind power penetration. From this analysis, an aggregated EV battery storage of 16 MW capacity supported (through V2G) 42 MW of wind power penetration into the power grid while without using EV to provide V2G services only a wind integration of 20 MW into the electric grid would be possible. With an aggregated V2G capacity of 16 MW, it was possible to integrate 82% and 70% of wind energy power of the total installed capacity for hourly and short time dynamic simulation, respectively. And in both scenarios, the V2G managed to efficiently support frequency stability. An interesting study on large integration of the RES (especially wind) into the Northeastern Brazil power system using PHEVs was conducted in [65] for the years 2015 and 2030 projections. The authors used governmental PHEV fleet which was assumed to be highly controllable in their driving patterns by the fleet personnel. As reported from this study, the option possesses two faces. First, the charging behavior can be easily managed to reduce the stresses on the power system and second, the incorporation of the smart grid technology can also be avoided to reduce initial cost. In year 2020, with 500 thousand PHEVs there could be an increase of the wind power capacity by 4%. Although the smart technologies were not considered in this study, a clear comment made is that smart metering and other communication technologies are inevitable for the efficient EV and WECS integration in the electric power grid.

A study on large integration of wind energy systems into the microgrid (MG) using PHEVs was conducted in [66]. The energy dispatching strategy is proposed to meet the dynamic power demands. The approach features a coordinated wind-PEV scheme that optimizes the effective utilization of these energy sources. It is observed that the power produced from the wind energy systems and corresponding consumption in the MG without taking into account PEVs indicates a big mismatch between the forecasted power and consumption over a day. This is due to the fact that the surplus power generated is not consumed by available loads. However, with the PEVs in place, the matching performance is highly enhanced. In this case, the PEV charging and discharging (V2G) process balances the power profile. Similarly, an interesting study by Liu et al. [67] adopted a two-stage stochastic unit commitment model that considers the interactions of the thermal generating units, PHEVs and large scale wind power systems. The study revealed that intelligent scheduling of the PHEVs significantly reduces the operating costs of the power systems and balances the fluctuations of the wind power generators. It is important to mention that with these studies the battery life cycles and PHEV with different capacities and driving patterns have to be considered in order to increase reliability in the real world scenarios.

5. Feasibility of smart V2G system

The interaction of electric vehicles with an electric grid is an attractive research area which has drawn attention to a number of people in the academia, industrial, public and private research institutes. As presented in this paper, we have detailed various application schemes of the EV technology in the power market under the smart grid context. However, there are few practical projects or studies to cover the actual implementation of the interaction of the EVs with the smart grid to realize the V2G schemes in the real world. Numerous smart grid and V2G technologies necessary to integrate electric vehicles into the smart grid in an efficient manner are yet under development stages. This includes battery technology, communication and power interfaces as a few to mention [68]. Besides, the intensive research and development are required to enhance the efficiency and lower the cost of various technologies like the EV charging infrastructures. Research activities and pilot projects initiatives are already in place to escalate the V2G concept into reality. Early pilot project was pioneered by Kempton et al. [69] for the EVs to feed the grid (V2G) in order to provide a real-time frequency regulation. The project demonstrated various possibilities of the V2G deployment to support the grid. However, it involves a single EV; in this case it is very tricky to conclude the results for a large EV fleet scenario.

5.1. Intelligent EV scheduling

The emergence of the EVs poses a great challenge on recharging their batteries as the EVs impact the grid by increasing load demand. It can be summed up that if charging of the EVs in some way is intelligently coordinated then a big shift of the load can be distributed. However, this requires a great deal of advanced control and communication incorporated for both parties; the grid side management system, market operators and EV management system.

One of the options proposed to alleviate the overloading of the distribution system due to EV charging is by introducing smart charging schemes discussed in the previous chapters. The concept is conceivable recently as the smart grid technologies penetrate into the existing power system together with the adoption of the smart grid test-beds.[1] The availability of wireless communication, GPS facility and smart metering infrastructures in the smart grid framework is becoming more apparent. Wireless connectivity in vehicles is extensively becoming a prevalent experience. The European Union (EU) enforcement regulation on the automatic crash notification (ACN) by the year 2015 for road safety and quick emergency response is one of the sailing boats to enhance communication between vehicle and infrastructure (V2I).[2] Hence, the smart charging technology and communication facilities will be envisioned as an extended service to this wireless

[1] Korea Smart Grid Institute (KSGI). http://smartgrid.or.kr/10eng3-3.php.

[2] http://www.telematicsresearch.com/PDFs/TRG_ITSWG-Telematics.pdf.

infrastructure in place. The smart meter can be configured as firmware rather than hardware while encapsulating roaming services to cope with the EV mobility nature for the dynamic pricing and other data exchange purposes to enable intelligent EV scheduling.

A body of research institutes and organizations is embarking on the programmes to integrate EVs into the smart grid. An international company called Better Place pursues a number of projects that demonstrates the electrification of transport sector from vision to reality; such projects include battery switching stations (BSS). In this case, the EV battery pack can be readily swapped with the fully charged battery packs from the BSS and the EV can continue with the daily activities. Hence, the process at the battery switching station increases the reliability of the EVs fleet. It is noted that in just 5 min one can swap the batteries and continue with his normal business. These stations have been opened recently in Israel, China, Netherlands and Denmark in addition to that in Tokyo city, Japan.[3] Another pilot project named e-mobility is operating in three cities in Italy (Pisa, Rome and Milan) and pioneered by the Daimier and Enel companies. It involves around 100 smart EVs and 400 smart charging stations to be completed in December 2013.[4] The smart charging system in this project encapsulates smart meters from Enel Company with GPRS communication technology, RFID and PLC link between the EV and control center. These demonstration projects reveal the insights and possibility of the smart electrification of the transport sector.

5.2. Renewable energy sources integration using EVs

Using electric vehicles to support the integration of the renewable energy sources (RES) especially wind and PV solar energies is becoming a major research topic. Introducing the EVs to this role will highly support and enhance more penetration of the RES into the grid. However, this concept is cross-cutting which prompts for a more detailed analysis in both technical and cost–benefit justification. There are already some demonstration projects to assess the impacts and feasibility of the EV interaction with the RES. The Zem2All e-mobility pilot project inaugurated recently (April 2013) in Malaga city, Spain will be the largest V2G pilot project. It features 23 CHAdeMO DC fast charging points including 6 bidirectional chargers capable of providing V2G functionalities. The project comprises 200 EVs (Nissan Leafs & Mitsubishi iMiEV) compatible with the CHAdeMO DC-fast charging standard. To be precise, it makes up 229 EV charging points in total [70]. More importantly, the EVs will support the integration of the intermittent renewable sources by absorbing the excess power produced by the RES and supply back to the grid at the times of peak demand (i.e. V2G). This will demonstrate the real life scenario for the interaction of the EVs with electric power system incorporating the RES and fast charging for the V2G services. Fig. 9 [70] shows a detailed view of one of the charging stations in this Zem2All project in Malaga city.

5.3. V2G impacts, potential and limitation

The electric vehicles are usually aggregated and treated as dynamic distributed energy sources in the V2G schemes to support the electric grid by providing ancillary services. A number of studies have shown the superiority of this concept and proved to be a better choice for future power system model as discussed previously. The deployment of the ESSs to balance the electric grid is not a new concept, and the energy sources like dedicated battery

Fig. 9. CHAdeMO chargers including bidirectional charger technology for V2G in Zem2All project, Malaga city [70].

storage systems, pumped hydroelectric storage, fly wheel and concentrating solar power (CSP) are among the technologies used. These are competing with the V2G penetration in the energy market. For instance, the pumped hydroelectric storage is considered to be much cheaper option than the V2G. The CPS as an energy storage system has higher efficiency up to 99% and can store energy for quite long time as compared to the EV battery pack [71,72].

Studies show that the CPS plant as energy storage unit for supporting the peak demand and regulation is quite appealing as the technology keeps on maturing. The world's largest CSP plant of 100 MW capacity has been recently inaugurated in Abu Dhabi, UAE. The penetration of the CPS and other energy sources into the power system grid is expected to increase as projected by the International Energy Agency (IEA). This prompts for an intensive research to justify the economic feasibility of the EVs for the V2G transactions as compared to these potential energy storage units.

Furthermore, the V2G schemes have shown an auspicious solution to the energy market. The primary goal for the EV adoption in the world is to replace fossil fuels from powering the normal internal combustion vehicles. Introducing the V2G transactions prompts for the upgrading of the EV technology to accommodate this extended application in the power market. The technology upgrade includes but not limited to bidirectional power converters, advanced communication, smart meters and new market players. Besides, the EV manufacturers have not yet introduced much of the EV-enabled cars for the V2G services because the EV owners will also have to decide to enter into those contracts or refrain from the new market opportunity (i.e. V2G). The question is, manufacturers should produce the EV with two variants (normal EV and EV-enabled for V2G) or single variant with two options, in the latter option it is obvious that an extra cost will be incurred (i.e. the technology remains redundant to the owner who will be reluctant to join the energy market). This is tricky and can divide the market share. Studies and researches are required to merge this gap of uncertainties while providing a feasible option to both parties; that is manufactures and/or customers before energy market players.

Most of the recent researches on the V2G deployment have centered their focus and analysis under the consideration of the deregulated electric market, in which the price tag of electric demand varies depending on the electricity producers (e.g. Generation Companies) or market players (e.g. energy brokers). These price variations (bidding) are optimized in the literatures to reduce the charging cost or even investment cost of the V2G or power distribution infrastructures [73]. In this case, the V2G transactions have been proved to be economically viable and technically

[3] http://betterplace.com/global/progress.
[4] http://www.smartgridsprojects.eu/map.html.

feasible in terms of the EV scheduling. Studies on different energy markets are becoming important to globally adopt the EV technology and fully utilize its potential. For example, Foley et al. [74] assesses and presents the impacts of the EV charging in the single wholesale electricity market operation with a case study of the Republic of Ireland. It is worth noting that an EV fleet has different impacts on the different electricity markets such as deregulated or regulated (monopoly) one. We anticipate that between the years 2020 and 2030, there will be a significant penetration of the EVs into the vehicle market. With the same projection, the V2G technology will also be matured. Many countries will adopt this technology but they already have different electricity market operation. For instance, electricity market in the Republic of Korea adopts the regulated power market while the US partly adopts the deregulated energy market. The comparative studies to assess the impact and feasibility of the EVs interaction with the grid at different energy market are imperative but have not yet drawn attention to a large extent recently.

As analyzed in the previous sections, it is clear that EV adoption into the power system will be visualized in the same way as dynamic distributed energy sources within the context of the virtual power plant (VPP). And the other functionalities like virtual STATCOM (STATCOM) will be possible [75]. In this case, they will support the integration of renewable energy sources especially wind and PV solar energies. Researches on these areas are critical to explore the benefits and enhance the mutual relation with the smart grid. The V2G services on the grid will widen the shift of the power system to the efficient virtual power grid.

6. Conclusion and future trends

This paper has presented an intensive review of the interaction of electric vehicles in the smart grid infrastructure. The integration of the renewable energy sources using EVs has also been discussed. It has been observed that electric vehicles can provide ancillary services to the grid such as voltage and frequency regulation, peak power leveraging and reactive power support to enhance the operational efficiency, secure the electric grid and reduce power system operating cost. The study has shown that the deployment of the EVs into the smart grid system would be possible with the advanced communication, control and metering technologies. In this case the smart grid will foster the interoperability of the EVs for the grid support. Following that note, a correlation between the smart grid and the EVs has been extensively investigated in this paper. However, more research and analysis are required to justify the adoption of the V2G framework over other energy storage systems. To realize a near-real time communication and power measurement, an advanced technology in these areas has to be enforced to identify the challenges and limitations. Few researches have been reported but the issues like communication delays, routing protocols and cyber security are very critical for the reliable and efficient adoption of the V2G transactions framework in the smart grid context.

Moreover, the feasibility of the smart grid with the V2G schemes has been explored with the insight of the recent projects. The low penetration of the electric vehicles embedded with the V2G functionalities is one of the challenges which hinder to a large extent the EVs adoption in the energy market. The side effects of the EV technologies like low cost and high efficient power converters (for EV charger) are among the other factors manifested at the automotive manufacturers' perspectives. For the effective V2G operation with the current battery technology, the challenge still remains to be battery wearing under frequent charging and discharging cycles. The researches have shown some promising results for lithium ion (LFP) battery. Nevertheless, to guarantee high penetration of the EVs, further detailed studies are required that would take into account various research areas like the strategies to enhance battery lifetime extension and cost–benefit analysis for their (batteries) deployment in the V2G services. Besides, the same studies on the other battery technologies like NiMH and various other lithium ion chemistries are yet to be revealed. This is an important topic as it involves the core technology for the EV applications especially the V2G services.

However, in the V2G applications, the dynamics of the power system (e.g. voltage dips) are inevitable. Studies on the V2G that consider weak grid dynamics are quite important but very few have been reported. Likewise, the integration of the RES into the power system such as wind and solar energy sources using EVs is one of the good representation models that require weak grid scenarios to be considered. To foresee the effective and reliable electric grid operation with the V2G support, a clear understanding of the dynamic behaviors of the electric grid is indispensable.

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